Drift-Shell Splitting in an Asymmetric Magnetic Field

Mei-Ching Fok

Universities Space Research Association, NASA Goddard Space Flight Center, Greenbelt, Maryland

Thomas E. Moore

Laboratory for Extraterrestrial Physics, NASA Goddard Space Flight Center, Greenbelt, Maryland

In a day-night asymmetric magnetic configuration, charged particles with different pitch angles gyrating along the same field line at one local time will be mirroring on different field lines as they drift to other local times. This drift-shell splitting effect is one of the important factors in determining the particle pitch angle distribution at distances greater than 5 earth radii. In this paper, the ring current ion pitch angle distribution is calculated in an activity-dependent Tsyganenko model, during the magnetic storm on May 2, 1986. Our simulation shows that, near the storm maximum, the observed low-energy (< 10 keV) pitch angle distributions on the dayside are strongly affected by drift-shell splitting. We also found that a fluctuating magnetic configuration produces diffusion in pitch angle, and that this effect is pronounced only for high-energy ions. Excellent agreement with the measured pitch angle distributions is obtained when a time-dependent realistic field model is employed.

1. INTRODUCTION

In a longitudinally uniform magnetic field (i.e., a pure dipole) and in the absence of electric field, charged particles with different equatorial pitch angles, originally mirroring along the same field line at one local time, will find themselves bouncing along the same field line when they drift to other local times. However, in reality, especially beyond 5 earth radii, the magnetic field is not day-night symmetric. In an asymmetric configuration, particles initially on the same field line but with different mirroring points will drift on different drift shells and spread over a region of field lines [*Roederer*, 1967]. Equivalently, particles with different pitch angles seen at one observation point may come from different locations. As a result, any pitch angle diffusion will lead to a radial diffusion owing to drift-shell splitting and vice versa [*Roederer*, 1967]. The effect of drift-shell splitting is an important factor in determination of the pitch angle distribution (PAD) of charged particles. *Sibeck et al.* [1987] showed qualitatively that drift-shell splitting in the distorted nondipolar magnetic field during disturbed periods can generate butterfly (relative minimum at 90° pitch angle) and head-and-shoulder (excess of near 90° pitch angle particles) energetic particle PADs which appear in the dayside magnetosphere. Drift-shell splitting separates the high and low pitch angle particles from nightside injections as they move to the dayside magnetosphere. The higher pitch angle particles move radially away from the earth and particles with lower pitch angles follow more circular drift paths. They argued, consequently, that butterfly PADs form at the same geocentric distance as the injection and head-and-shoulder PADs at a point slightly further radially outward.

Geospace Mass and Energy Flow: Results From the International Solar-Terrestrial Physics Program
Geophysical Monograph 104

We have developed a kinetic model to solve the temporal variation of the ring current energy and pitch angle distributions in a magnetic dipole field [*Fok et al.*, 1995, 1996]. In the simulation of the main phase of the storm on May 2, 1986 [*Fok et al.*, 1996], we found, near the inner edge of the ring current, the observed perpendicular PAD is a result of strong charge exchange loss of the field-aligned ions. For energies greater than tens of keV, however, the observed round-shape PAD cannot be solely explained by the charge exchange loss. An additional pitch angle diffusion process with diffusion coefficient about 5×10^{-6} s^{-1} is required in order to match the data from AMPTE/CCE (Active Magnetospheric Particle Tracer Explorers / Charge Composition Explorer) satellite. Recently, our model has been extended to include a realistic magnetic field model [*Tsyganenko*, 1989]. This improved ring current model was used to simulate the sudden enhancements in the equatorial ion fluxes and the corresponding ionospheric precipitation during a substorm expansion [*Fok and Moore*, 1997]. In the present paper, the effects of drift-shell splitting on the ring current pitch angle distribution are studied using our model with an asymmetric magnetic field. The main phase of the storm on May 2, 1986 is simulated. The calculated PADs are compared with those results generated in a dipole field to distinguish the shell-splitting effects. Observed ring current H^+ PADs by the AMPTE/CCE satellite will be used to evaluate the success of the modeling approach.

2. PREVIOUS CALCULATIONS IN MAGNETIC DIPOLE FIELD

We have previously modeled the H^+ pitch angle distribution in a magnetic dipole field during the main phase of the storm on May 2, 1986 [*Fok et al.*, 1996]. The initial condition is a quiet time distribution. The H^+ differential flux averaged over pitch angle compiled by *Sheldon and Hamilton* [1993] during the quietest days in 1985–1987, seen by CCE is used as initial distribution at 0200 UT, May 2, 1986. Another input to the model is the boundary condition near geosynchronous orbit. The instantaneous energy and pitch angle distributions on the nightside boundary (r_0 ~ 6.75) are obtained by interpolation in time of measurements from two CCE passes at 0800 and 2400 UT, where r_0 is the equatorial distance in earth radius (R_E).

The initial ion PADs are estimated by radial distance and the charge exchange cross sections with the neutral hydrogen, assuming that the quiet time PAD is mainly shaped by the charge exchange loss [*Fok et al.*, 1996]. Figure 1 plots the initial PAD of H^+ (dotted lines) of 4

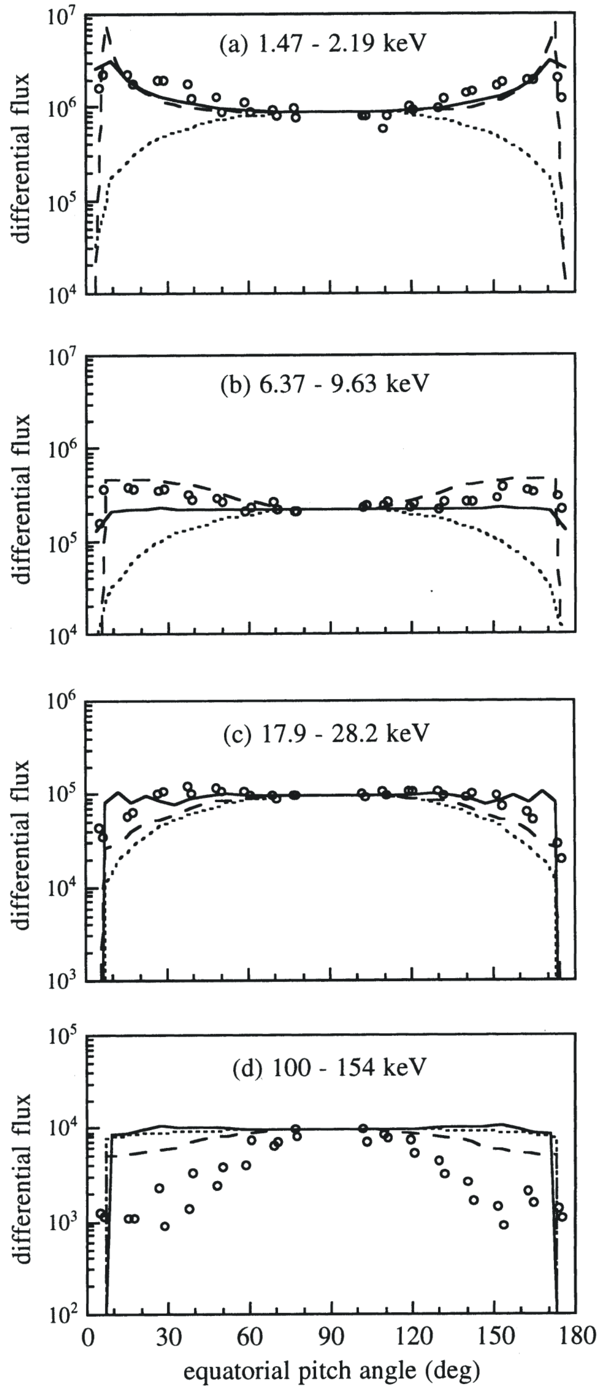

Figure 1. Calculated pitch angle distributions in a dipole field (solid lines) and in a Tsyganenko model (dashed lines) at ~ 1800 UT, 5.7 R_E, 0800 LT. Open circles are observations from AMPTE/CCE at the same location and time, on May 2, 1986. Dotted lines are the initial distributions at 0200 UT. All data sets are scaled so that they match at 90° pitch angle.

different energies at $r_o \sim 5.7$. The round shape PADs of the low energy H^+ (Figure 1a, b, and c) represent relatively strong charge exchange loss of field aligned ions at these energies. The charge exchange cross section of H^+ decreases with increasing energy, so the initial PAD of the 100–154 keV ions are fairly isotropic. After 16 hours of simulation, the calculated dayside PADs at 0800 UT in a dipole field at the same radial distance are overlaid in Figure 1 in solid lines. The CCE measurements at the same time and location are also shown in open circles. The representation of the dashed lines will be discussed in the later sections. Charge exchange loss is not strong at this distance. If the magnetic field is a pure dipole and thus there is no drift-shell splitting, the shape of the dayside PAD should be similar to that on the nightside. As shown in the Figure 1 (solid lines), we predict a field-aligned distribution in the lowest energy range and flat distributions for higher energies. These simulated PADs on the dayside strongly depend on the corresponding distributions measured on the nightside boundary. However, observations on the dayside (open circles) show a field-aligned distribution in the energy range of 6.37–9.63 keV and perpendicular distributions for energies $\gtrsim$ 20 keV. As we have suggested, additional processes must be taken into account to determine the ion pitch angle distributions.

3. RING CURRENT MODELING IN REALISTIC MAGNETIC CONFIGURATION

Our ring current model has been extended to adapt any magnetic field configuration [*Fok and Moore*, 1997]. In the new version of the model, particle drifts are calculated in the coordinates spanned by two Euler-potentials: (α, β). We have chosen $\beta = \phi_i$ and $\alpha = -M_E \cos 2\lambda_i / 2r_i$, where M_E is the Earth's magnetic dipole moment; λ_i, ϕ_i and r_i are the magnetic latitude, magnetic local time and radial distance, respectively, of the ionospheric foot point of the field line. We have used the ionospheric foot point to label a field line since magnetic variation at the ionosphere is very small even when the magnetosphere is compressed or expanded due to substorm activities. Field lines thus can be regarded as rooted at the ionosphere.

The bounce-averaged drift of a charge particle can be represented by [*Northrop*, 1963]:

$$\langle \dot{\alpha} \rangle = -\frac{1}{q}\frac{\partial H}{\partial \beta}\,,\ \langle \dot{\beta} \rangle = \frac{1}{q}\frac{\partial H}{\partial \alpha} \tag{1}$$

where H has the form:

$$\begin{aligned} H &= \sqrt{p^2c^2 + m_o^2c^4} + q\Phi + q\alpha\,\partial\beta/\partial t \\ &= \sqrt{p^2c^2 + m_o^2c^4} + q\Phi + q\alpha\Omega \end{aligned} \tag{2}$$

Φ is the cross-tail potential and Ω is the angular velocity of the rotation of the Earth. $\langle \dot{\alpha} \rangle$ and $\langle \dot{\beta} \rangle$ include gradient-curvature drift, electric drift due to convection, and corotation. The convection model employed is that of Volland-Stern [*Volland*, 1973; *Stern*, 1975], with the field strength parameterized by the *Kp* index [*Maynard and Chen*, 1975]. The changing of the magnetospheric configuration during substorms do not yield any non-zero value of $\partial\beta/\partial t$ $(= \partial\phi_i/\partial t)$ because we have assumed that the ionospheric foot points of field lines are unchanged due to substorm activities. The substorm induced electric field and the resulting bounce-averaged drift are treated implicitly by continuously changing the gradient-curvature drift according to the instantaneous magnetic configuration.

It is convenient to express the bounce-averaged velocity in terms of λ_i and ϕ_i,

$$\langle \dot{\lambda}_i \rangle = -\frac{1}{q\xi}\frac{\partial H}{\partial \phi_i}\,,\ \langle \dot{\phi}_i \rangle = \frac{1}{q\xi}\frac{\partial H}{\partial \lambda_i} \tag{3}$$

where ξ is equal to $M_E \sin 2\lambda_i / r_i$. The bounce-averaged kinetic equation of ring current ion species s is given by [*Fok and Moore*, 1997]:

$$\frac{\partial \bar{f}_s}{\partial t} + \langle \dot{\lambda}_i \rangle \frac{\partial \bar{f}_s}{\partial \lambda_i} + \langle \dot{\phi}_i \rangle \frac{\partial \bar{f}_s}{\partial \phi_i} = -v\sigma_s \langle n_H \rangle \bar{f}_s - \left(\frac{\bar{f}_s}{0.5\tau_b} \right)_{\text{loss cone}} \tag{4}$$

where $\bar{f}_s = \bar{f}_s(t, \lambda_i, \phi_i, M, K)$, is the average distribution function on the field line between mirror points. M is the relativistic magnetic moment and $K = J/\sqrt{8m_oM}$. σ_s is the cross section for charge exchange of species s with the neutral hydrogen and n_H is the hydrogen density. τ_b is the bounce period. The second term on the right hand side of (4) is applied only to particles with pitch angle inside the loss cone, which is defined at 800 km. In this study, only loss due to charge exchange with the neutral hydrogen and loss at the loss cone are considered.

4. DRIFT-SHELL SPLITTING IN ASYMMETRIC MAGNETIC FIELD

The H^+ pitch angle distributions at various energies are re-calculated in a realistic magnetic field model with the

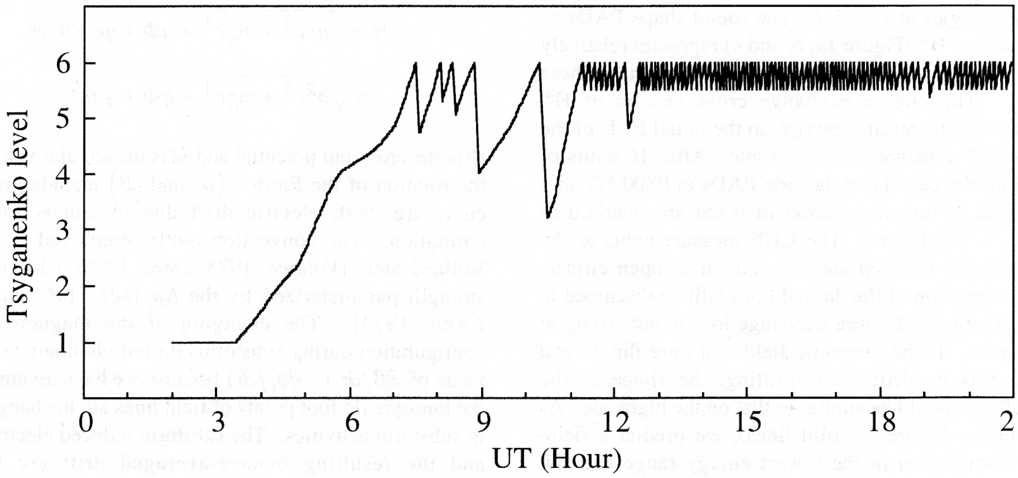

Figure 2. Simulated levels (IOPT) of the Tsyganenko model as a function of UT on May 2, 1986.

same initial and boundary conditions used in *Fok et al.* [1996] for the May 2, 1986 storm. The magnetic field configuration is represented by the Tsyganenko model at various activity levels (EXT89AE, IOPT = 1–6). An algorithm has been established to simulate the instantaneous magnetic field configuration driven by the *AE* index [*Fok et al.*, 1996]. The simulated Tsyganenko level (IOPT) as a function of UT on May 2, 1986 are plotted in Figure 2. Simulation starts when the magnetosphere is in quiet condition (level = 1). The magnetosphere then slowly evolves to the higher levels (increased stretching and inflation). When it reaches the level of 6, it collapses to lower levels. At the early main phase (before 1100 UT), the rate of stretching is small and the amplitude of relaxation is large. However, during the highly disturbed period, the magnetosphere is rapidly stretched and only small relaxations occur. The bounce-averaged drift velocities $\left(\langle\dot{\lambda}_i\rangle \text{ and } \langle\dot{\phi}_i\rangle\right)$ are calculated according to the instantaneous magnetic field configuration. Velocities at continuous levels are obtained by interpolation between the 6 discrete levels.

We overlay on Figure 1 the calculated PADs (dashed lines) in the Tsyganenko field at the same time and location (1800 UT, 5.7 R_E, and 0800 LT) as those previously obtained in a dipole field. Both sets of calculated fluxes are scaled to match the measurements at 90° pitch angle. As shown in the figure, for ion energy below 10 keV (Figure 1a, b), more field-aligned distributions are predicted in an asymmetric field than in a dipole field. We have traced backward along the drift paths of particles with different equatorial pitch angles. We found these low-energy ions drift along open trajectories and reach the observation point from dawn. However, field-aligned particles come from the local times farther toward nightside than field-perpendicular particles. The new simulation predicts more field-aligned ions at this observation point because they come from closer to the nightside injection region. With the consideration of an asymmetric field, great improvement has been made in agreement with the observation, especially in the energy range of 6.37–9.63 keV.

Figures 1c and 1d show the results in energy ranges of 17.9–28.2 and 100–154 keV. In these two cases, including a realistic magnetic field model gives rounder pitch angle distributions. It seems that a diffusive process in pitch angle is taking place to smooth out the distribution. Ions at these energies exhibit closed drift paths and diffusive transport dominates their motions [*Chen et al.*, 1994]. We suspect that the fluctuation of the magnetosphere (see Figure 2) during the late main phase produces particle radial diffusion, as well as pitch angle diffusion. Our suggestion is confirmed when we perform a test run with Tsyganenko level kept at a constant of 5.5 after first reaching this value at ~ 0700 UT. The test simulation gives relatively flat (with respect to the dashed line in Figure 1c, d) distributions for both 17.9–28.2 keV and 100–154 keV ions. In other words, without the high-frequency (~ 10 hr^{-1}) fluctuating magnetic field, the round shape PAD for high-energy ions cannot be reproduced. Of course, even with the time-varying magnetic field, the observed strong perpendicular PAD for 100–154 keV ions is not accurately predicted (Figure 1d). Other processes that cause pitch angle diffusion, such as wave-particle interactions and electric fluctuation, should also be considered. For ions below 10 keV, there is nearly no difference between the calculated PADs from the test simulation and those from the fluctuating magnetic field. This indicates that diffusive transport of low-energy ions is unimportant.

5. DISCUSSION AND SUMMARY

The effect of drift-shell splitting on the ring current ion pitch angle distribution has been modeled in an activity-dependent Tsyganenko magnetic field model. We compare the calculated PADs in a realistic field at 5.7 R_E with those previously calculated in a dipole configuration and find significant differences. Moreover, great improvement is obtained in agreement with the CCE particle observations with the asymmetric magnetic field.

We have quantitatively shown that magnetic fluctuations result in pitch angle scattering. We plan to simulate the diffusive effect from electric variations as well. In future work, a realistic electric field model based on interplanetary magnetic field and solar wind conditions [e.g., *Weimer*, 1995; *Papitashvili*, 1994] will be incorporated in our model. The role of wave-particle interactions on ring current distribution will also be investigated.

In conclusion,

(1) We have calculated the ring current ion pitch angle distributions in a day-night asymmetric magnetic field model during the main phase of the storm on May 2, 1986.

(2) We found drift-shell splitting is responsible for the observed dayside field-aligned PADs for low-energy (< 10 keV) ions.

(3) We have shown that drift-shell splitting in a fluctuating magnetic configuration results in pitch angle diffusion for high-energy (> 20 keV) ions.

REFERENCES

Chen, M. W., L. R. Lyons, and M. Schulz, Simulations of phase space distributions of storm time proton ring current, *J. Geophys. Res., 99*, 5745-5759, 1994.

Fok, M.-C., and T. E. Moore, Ring current modeling in a realistic magnetic field configuration, *Geophys. Res. Lett., 24*, 1775-1778, 1997.

Fok, M.-C., T. E. Moore, J. U. Kozyra, G. C. Ho, and D. C. Hamilton, Three-dimensional ring current decay model, *J. Geophys. Res.*, 9619-9632, 1995.

Fok, M.-C., T. E. Moore, and M. E. Greenspan, Ring current development during storm main phase, *J. Geophys. Res.*, 101, 15,311-15,322, 1996.

Maynard, N. C., and A. J. Chen, Isolated cold plasma regions: Observations and their relation to possible production mechanisms, *J. Geophys. Res., 80*, 1009-1013, 1975.

Papitashvili, V. O., B. A. Belov, D. S. Faermark, Ya. I. Feldstein, S. A. Golyshev, L. I. Gromova, and A. E. Levitin, Electric potential patterns in the Northern and Southern polar regions parameterized by the interplanetary magnetic field, *J. Geophys. Res., 99*, 13,251-13,262, 1994.

Roederer, J. G., On the adiabatic motion of energetic particles in a model magnetosphere, *J. Geophys. Res., 72*, 981-992, 1967.

Sheldon, R. B., and D. C. Hamilton, Ion transport and loss in the earth's quiet ring current 1. Data and standard model, *J. Geophys. Res., 98*, 13,491-13,508, 1993.

Sibeck, D. G., R. W. McEntire, A. T. Y. Lui, R. E. Lopez, and S. M. Krimigis, Magnetic field drift shell splitting: cause of unusual dayside particle pitch angle distributions during storms and substorms, *J. Geophys. Res., 92*, 13,485-13,497, 1987.

Stern, D. P., The motion of a proton in the equatorial magnetosphere, *J. Geophys. Res., 80*, 595-599, 1975.

Tsyganenko, N. A., A magnetospheric magnetic field model with a warped tail current sheet, *Plant. Space Sci., 37*, 5-20, 1989.

Volland, H., A semiempirical model of large-scale magnetospheric electric fields, *J. Geophys. Res., 78*, 171-180, 1973.

Weimer, D. R., Models of high-latitude electric potentials derived with a least error fit of spherical harmonic coefficients, *J. Geophys. Res., 100*, 19,595-19,607, 1995.

M.-C. Fok, and T. E. Moore, Lab. for Extraterrestrial Physics, NASA/GSFC, Code 692, Greenbelt, MD 20771. (e-mail: fok@gsfc.nasa.gov, thomas.e.moore@gsfc.nasa.gov)